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Frequency Extraction of Current Signal Spectral Components: A New Tool for the Detection of Rotor Electrical Faults in Induction Motors

P. A. Panagiotou, I. Arvanitakis, N. Lophitis, *Member, IEEE* and K. N. Gyftakis, *Member, IEEE*

Abstract— This work expands the classical current signature analysis in induction machines in a two-stage spectral decomposition manner. The proposed methodology can be summarized in two main steps: initially, the current signals are analyzed using a time frequency representation, with the analysis focusing on the steady-state regime; thereafter, frequency extraction is applied to the spectral signatures of interest, aiming to identify specific fault related harmonic subcomponents induced by the fault related speed ripple effect. The proposed approach is verified experimentally on a 4 kW induction motor.

Index Terms — broken bars, frequency extraction, spectral components, t-f analysis

I. INTRODUCTION

THE field of induction machines' condition monitoring has been rapidly advancing in the past few decades and adjusting to the complexity of the modern industrial demands, in order to assert safety, prevent downtimes or emergency maintenance and -of course- to obviate any potential financial casualties. Rotor faults are important to detect at early stages, since their appearance can progress internally affecting the rest of the cage and the rotor iron core.

For the detection and diagnosis of rotor faults, the early research in the field handled the monitoring of the line currents by examination of the signal anomalies over time or by examination of its frequency spectra [1]-[4]. The reason was the fact that the acquisition of a current measurement holds some advantages like: its reliability and low cost [4]-[5]; it can be done safely from a distance, since it is usually measured for control and stabilization purposes [5]; its non-intrusive character and low computational complexity [5]-[7] and -most importantly- it can be applied on-line [3]-[7]. This was the stepping-stone for the commercially established monitoring equipment applying Motor Current Signature Analysis (MCSA) and also for the archiving of the first actual

on-field industrial history case-studies by means of currents [4]-[7].

Subsequently, the theoretical background and analytical modelling approaches on the harmonic content started to update [8]. However, in the light of reports mentioning some MCSA deficiencies [4], the knowledge on specific fault related harmonic components and their mechanisms required further investigations and updating [9]-[11]. In sequence, questions were raised for the adequacy of classical signal processing techniques like the Fast Fourier Transform (FFT) [12]-[14]. This triggered the application of other types of analyses along with the reformation of stationarity/non-stationarity assumptions during fault conditions [15]-[17]. Developments to that direction include: the Hilbert Transform [14], [18]-[19], envelope analysis [20], the Wavelet Transform [21]-[23] and other time-frequency representations by means of transforms (Gabor [24], STFT [25]-[27], Adaptive Slope [28] etc.) or distributions (Wigner-Ville [29]-[30] etc.). Meanwhile, further options of measurements were also examined with success, like torque monitoring [31]-[32], stray flux signature analysis (SFSA) [33]-[35] and the zero-sequence current (ZSC) [36]. Some works like [3], [33] and [37]-[38] suggest the use of additional monitoring methods to be used complementary with MCSA for adequate and reliable diagnosis.

During the last decade, a series of more advanced approaches have been proposed for broken rotor bar detection. These include statistical-based approaches [39]-[40], classification techniques [41]-[42] and methods using machine learning tools [43], while the field continues to update with reported MCSA industrial case-studies [22], [44].

In the present paper, a newly introduced approach is presented for the reliable detection of rotor faults. Given the existing knowledge on frequency tracking with MCSA and the fault related signatures during broken rotor bars existence, a t-f representation is used on the phase current signals to visualize the signatures of interest. Accounting for the speed ripple effect, the spectral density information at steady state is individualized and extracted through the spectrogram for each harmonic of interest. The extracted spectral trajectories are then examined as periodical oscillations over time and

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their FFT is evaluated for the frequency tracking of fault-related subcomponents. The proposed method is validated via extensive 2D FEA simulations on a 4 kW induction motor and by experimental laboratory testing.

II. THEORETICAL BACKGROUND

A. Broken Bar Diagnostics: Classical MCSA & TCSEA

At the event of a bar breakage, the bar is electrically disconnected from the rest of the cage. Due to the asymmetry created by this open-circuit condition at the point of breakage, two counter-rotating magnetic fields of frequencies $\pm sf_s$ exist in the rotor [2]-[10], with s the motor slip and f_s the fundamental frequency (supply).

The chain reaction of harmonics over the frequency spectra due to the counter rotating field at $-sf_s$ and the genesis of fault related speed-ripple effect sidebands, is analytically described in [2]-[4], [10] and [23]. The equation for tracking the frequency signatures regarding broken bar faults is the following [12], [18], [21], [24]:

$$f_{bb} = \left[\frac{k}{p}(1-s) \pm s \right] f_s, \quad (1)$$

where: p : the pole pairs, s the slip and $k \in \mathbb{Z}$ such that $\frac{k}{p} \in \mathbb{Z}$.

Traditionally applied MCSA inspects the signatures of those harmonics over the FFT spectra to evaluate their amplitudes, while the motor is operating at the late steady-state. The sum of the fundamental harmonic's sidebands at $\pm 2sf_s$ is examined in [2], proven as a reliable diagnostic index for fabricated rotors. Broken bars are examined by MCSA means in [3], combined with instantaneous torque and instantaneous power accounting for speed and torque ripples. Combination of this knowledge is then used by the authors in [4], where rotor electric and magnetic asymmetries are deciphered for laboratory-scale motors and for industrial-orientated motors with "spider"-designed rotors. Moreover, [8] validates the theoretical and experimental frequency content for the stator and rotor space harmonics under healthy condition, one, two and three broken bars. A device for online monitoring of rotor faults using the two sidebands is presented in [10], while a novel approach for monitoring the sidebands' behaviour is proposed in [14] combining the classical FFT method with phase analysis via the Hilbert Transform. The sidebands amplitude and phase modulations are examined in [15] by MCSA means, while [20] presents a low-cost diagnosis framework for diagnosing rotor asymmetries at low slip values with reduced envelope analysis.

Nevertheless, the existence of a fault and its progression are governed by non-stationarity [17]-[19]. Except from the frequencies' evolution and transitions during the transient start-up, at the presence of a fault the machine is subjected to local transients. Even at the steady-state, the disturbances caused by a fault affect the signals' instantaneous frequency [13]-[19], or imply varying and oscillating amplitudes [14],

[15]-[17], [35], [40]. These drawbacks can be a vice when using MCSA on the pipeline for a diagnostic decision. Therefore, Transient Current Signature Analysis (TCSEA) [21]-[23] and similar approaches have been proposed [24]-[30]. These track the evolution of frequencies during the machine's start-up or other local transient parts as trajectories or orbits [12], [13], [21]-[30]; otherwise, they demodulate and decompose the studied signals' spectral components to examine if any diagnostic information is comprised in the instantaneous frequencies [14]-[19].

B. Time-Frequency Analysis & STFT

The STFT analysis is a commonly used time-frequency representation [25]-[27]. In its continuous form, the STFT $X(t, f)$ of a signal is given, as a function of both time t and frequency f , from the FFT over a sliding window [25], [35]:

$$X(t, \omega) = \int_{-\infty}^{+\infty} x(t)w(t - \tau)e^{-j\omega\tau}d\tau \quad (2)$$

$x(t)$ being the examined signal, $w(t)$ the sliding window, τ the window shift parameter and $\omega = 2\pi f$ the angular frequency. From (2), the spectral density is provided as a joint t-f representation via the spectrogram:

$$S(t, f) = |X(t, f)|^2 \quad (3)$$

For sampled and discretized signals, the discrete-time form of the STFT [49] is used as:

$$X[t, \omega] = \sum_{n=t-L/2}^{t+L/2} [x_n \cdot w_{n-t}] \cdot e^{-jn\omega}, \quad (4)$$

t and f the discrete time and frequency respectively, L the length of the window.

C. Windowing Limits & Spectral Components Extraction

The transformation for the STFT analysis is derived using a Kaiser window ($\beta = 18.13$) with 70.4% overlap between the frames. The parameters were selected to keep optimized two factors: a windowing with unitary ripple response, as close as possible to rectangular shape; secondly a satisfying frequency resolution. The latter is wished to clearly observe the trajectories on the spectrogram [26]-[27], [45]-[46].

Taking advantage of the ripples circled with dashed lines in Fig. 1, the spectral components are extracted for a desired frequency -e.g. the 5th harmonic and its $(5 - 4s)f_s$ and $(5 - 6s)f_s$ sidebands- using frequency extraction [35], [46]-[49]. The spectral density information carried in each extracted trajectory is then handled as a function of amplitude and time at this specific frequency. During this frequency extraction process, one should account for the harmonics' separability. This means that the windowing functions will yield a frequency resolution able to localize each trajectory in a different time-chunk or frequency-bin to prevent aliasing and spectral leakage diffusion between sidebands [48]. To ensure that, the windowing limits are derived as in [46] and [49], to separate harmonics distanced at least $2sf_s$ from each other.

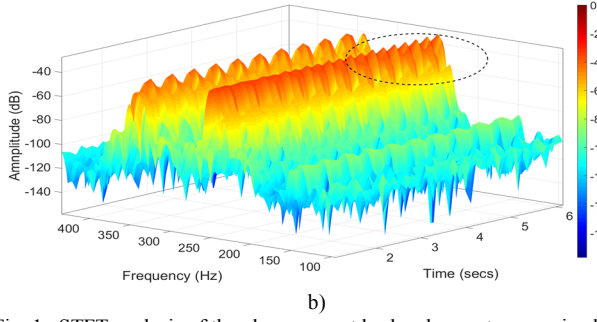


Fig. 1. STFT analysis of the phase current broken bar motor examined with FEM around the 5th harmonic area.

The fault related components are extracted by (3) and their spectral content at a desired frequency over time is yielded:

$$S(t, f_{a,i}) = |X(t, f_{a,i})|^2, \quad (5)$$

$f_{a,i}$ being the component of the a -th harmonic and $i = 1, 2$.

III. TECHNICAL WORK & DATA COLLECTION

A. FEM Models

An induction machine has been designed with MagNet FEM software from Mentor/Infologic. Two different models were simulated: the healthy one and the one with 1 broken rotor bar using the Transient 2D solver in Motion analysis (rotary load-driven), a type of simulation accounting for the machines' motion equation, rotor inertia and speed ripple effect. The motors are tested at full load, which is the constant rated torque load in each case. The motors' geometrical model is presented in Fig. 2 along with the spatial distribution of the magnetic flux density during faulty condition. The motor's characteristics are described in Table I.

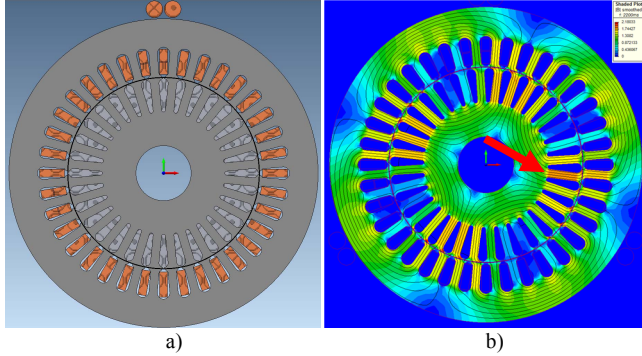


Fig. 2. a) Geometrical solid model of the induction motor and b) spatial distribution of the magnetic flux density \mathbf{B} (T) under broken rotor bar fault.

TABLE I
CHARACTERISTICS OF THE SIMULATED MOTORS

Frequency	50Hz
Stator Connection	Δ
Rated Power	4 kW
Rated Voltage	400 V
Rated Current	10 A
Pole pairs	2
Rated Load	26 Nm
Stator slots	36
Rotor slots	28

B. Experimental Set-up

The experimental set-up is shown in Fig. 3. Two identical 50 Hz, 400 V, 4 kW and 4-pole induction motors have been used during the experimental validation: the healthy and one with the rotor drilled in order to electrically disconnect the bar from the cage. The motors are mechanically coupled to a permanent magnet generator feeding a Y-connected, symmetrical, 3-phase variable resistance. The induction motor's stator winding is connected in Δ .

For the current measurements, three identical current sensors were used. The measurements were logged onto a high resolution, deep memory, 8-channel oscilloscope. Each signal waveform was captured in a frame of 20 sec, providing reliable signal representation in time and frequency domain with a sampling frequency of 10 kHz.



Fig. 3. Experimental set-up.

IV. RESULTS & DISCUSSION

A. FEM Results

The extracted spectral information over time regarding the trajectory of the 5th harmonic's lower sideband at $(5 - 4s)f_s$ is depicted in Fig. 4. From a first inspection it is evident that the healthy model's trajectory (blue) is oscillating at a constant small ripple, while the ripple of the faulty case is increased and indicative for the existence of a rotor fault. The trajectories' FFT spectra are presented in Fig. 5 for the 5th harmonic and in Fig. 6 for the 7th harmonic.

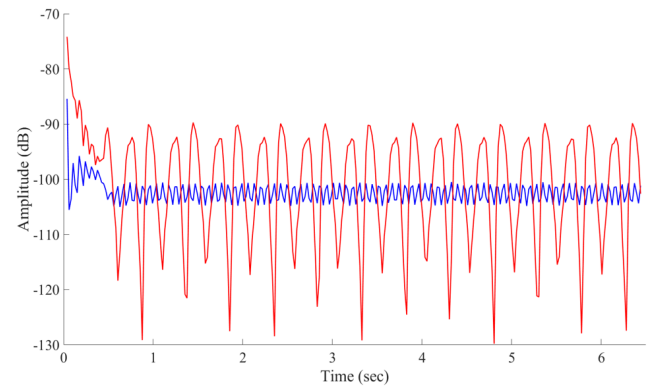


Fig. 4. The extracted $S(t, f_{a,i})$ amplitude information for healthy (blue) and faulty (red) motors of the $(5 - 4s)f_s$ sideband extracted trajectory.

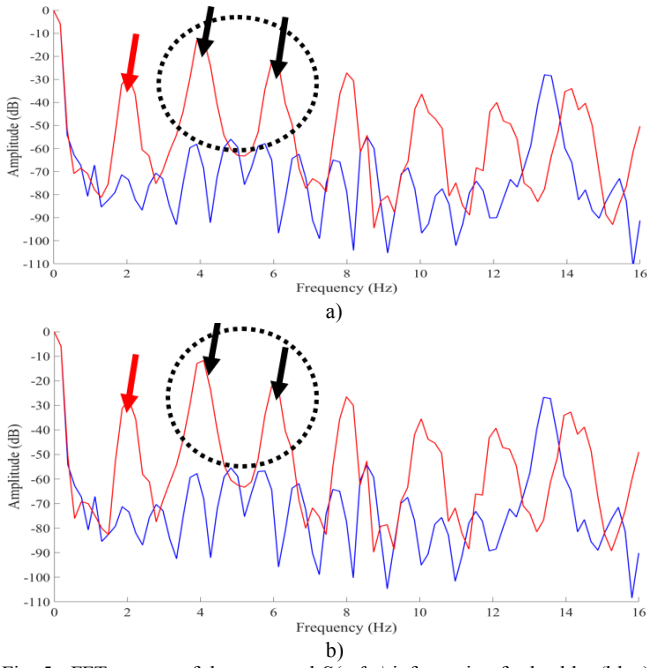


Fig. 5. FFT spectra of the extracted $S(t, f_{o,l})$ information for healthy (blue) and faulty (red) motor at: a) $(5-4s)f_s$ and b) $(5-6s)f_s$.

The amplitudes of the fault related pulsating components regarding both motors are shown in Table II and Table III for the 5th and the 7th harmonic respectively. The components of the faulty motor at frequencies $4sf_s$ and $6sf_s$ (black arrows) rise at the amplitudes of -12.01 dB and -23.63 dB respectively regarding the $4sf_s$ sideband. In the trajectory of the $6sf_s$ sideband, the amplitudes are -11.75 dB and -23.24 dB respectively (Table II). These components are practically inexistent in the healthy motor ($\leq -50 \text{ dB}$). Interestingly, the component at $2sf_s$ is inexistent in the healthy motor while present in the faulty motor. This is due to the fault-related speed ripple.

TABLE II
5TH HARMONIC EXTRACTED COMPONENTS (FFT AMPLITUDES)

Motor	$5fs - 4sf_s$		$5fs - 6sf_s$	
	$4sf_s$	$6sf_s$	$4sf_s$	$6sf_s$
Healthy	-58.11 dB	-57.88 dB	-57.78 dB	-56.71 dB
Faulty	-12.01 dB	-23.63 dB	-11.75 dB	-23.24 dB

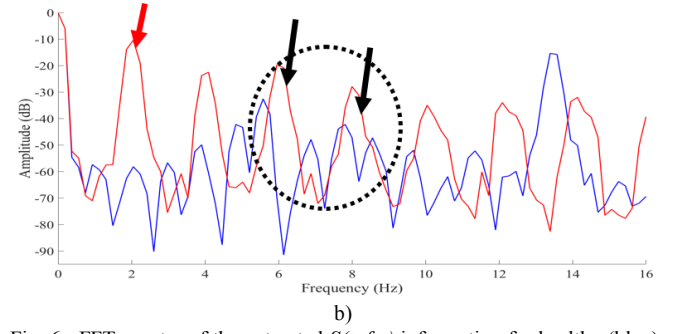
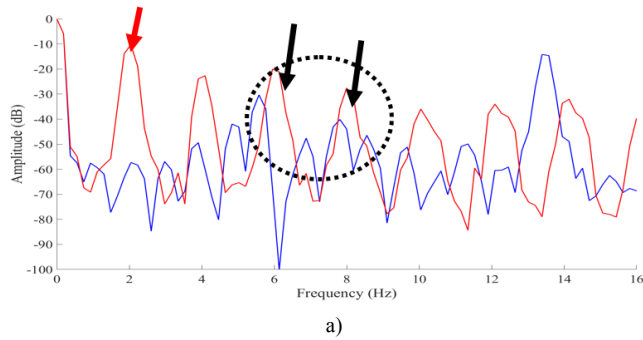


Fig. 6. FFT spectra of the extracted $S(t, f_{o,l})$ information for healthy (blue) and faulty (red) motor at: a) $(7-6s)f_s$ and b) $(7-8s)f_s$.

Similar indications are provided by the spectra of the 7th harmonic sidebands. The $6sf_s$ and $8sf_s$ components rise with amplitudes of -21.12 dB and -30.91 dB in the faulty motor regarding the signature $7fs - 6sf_s$. The extracted spectra of the signature $7fs - 8sf_s$ reveal amplitudes of the $6sf_s$ and $8sf_s$ components equal to -20.74 dB and -27.87 dB respectively, a rise of 12.53 dB and 19.35 dB respectively compared with the healthy motor.

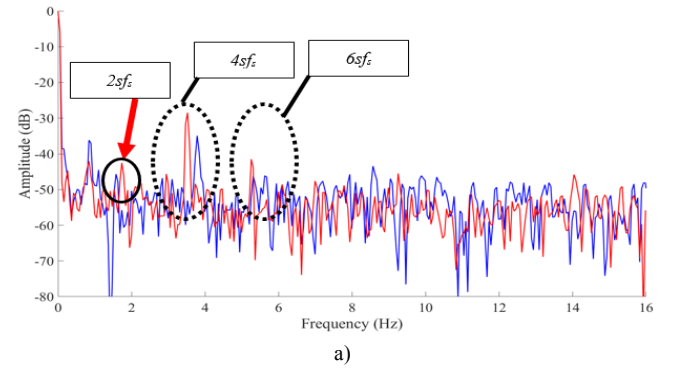
TABLE III 7 TH HARMONIC EXTRACTED COMPONENTS (FFT AMPLITUDES)				
Case	$7fs - 6sf_s$		$7fs - 8sf_s$	
	$6sf_s$	$8sf_s$	$6sf_s$	$8sf_s$
Healthy	-30.32 dB	-40.15 dB	-32.53 dB	-47.22 dB
Faulty	-21.12 dB	-30.91 dB	-20.74 dB	-27.87 dB

TABLE IV
SLIP OF THE FEM MOTORS (%)

healthy	0.021
faulty	0.019

B. Experimental Results

Regarding the experimental measurements, the trajectories' FFT spectra are presented in Fig. 7 for the 5th harmonic and in Fig. 8 for the 7th harmonic. The amplitudes of the components are shown in Table V and Table VI for the 5th and the 7th harmonic respectively for both motors.



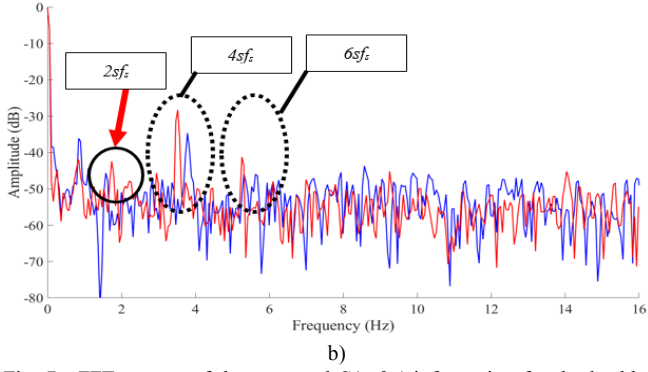


Fig. 7. FFT spectra of the extracted $S(t, f_{o,i})$ information for the healthy (blue) and faulty (red) motor at: a) $(5-4s)f_s$ and b) $(5-6s)f_s$.

TABLE V

5 TH HARMONIC EXTRACTED COMPONENTS (FFT AMPLITUDES)				
Case	$5f_s - 4sf_s$		$5f_s - 6sf_s$	
	$4sf_s$	$6sf_s$	$4sf_s$	$6sf_s$
Healthy	-34.93 dB	-46.18 dB	-34.69 dB	-45.91 dB
Faulty	-28.49 dB	-40.51 dB	-28.27 dB	-40.23 dB

The amplitudes of the examined components at $4sf_s$ and $6sf_s$ frequencies (circled in dashed in Fig. 7) rise at the amplitudes of -28.49 dB and -40.51 dB respectively regarding the lower 5th harmonic's sideband (Table IV). This implies a rise of 6.44 dB and 5.67 dB respectively, compared to the healthy motor. For the trajectory of the upper sideband, these spike at -28.27 dB and -40.23 dB respectively. Comparing it with the healthy motor, it is a rise of 6.42 dB and 5.68 dB respectively. Note that the component at $2sf_s$ is dimly present in the low frequency range for the healthy motor (red arrows in Fig. 7). This component is evident in the experiments, due to inherent cage asymmetries -like magnetic anisotropy or the cage porosity- which are not accounted for by 2D FEM. Hence, this component exists only in actual healthy motors, where these phenomena are implied by naturally existing manufacturing defects.

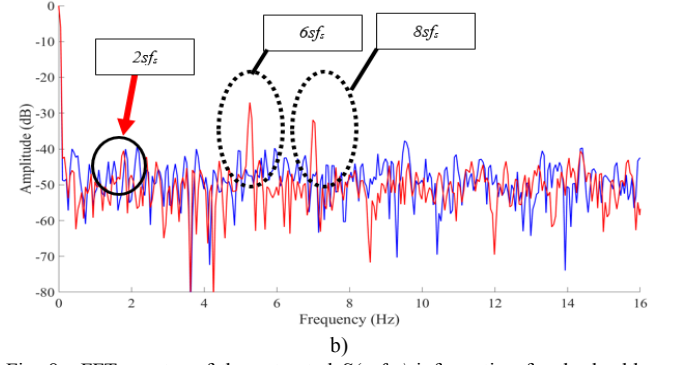
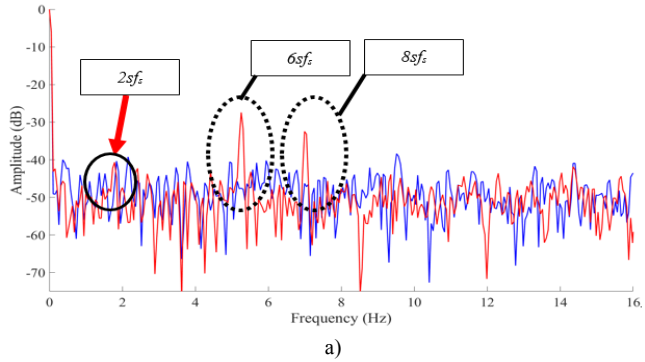


Fig. 8. FFT spectra of the extracted $S(t, f_{o,i})$ information for the healthy (blue) and faulty (red) motor at: a) $(7-6s)f_s$ and b) $(7-8s)f_s$.

TABLE VI

7 TH HARMONIC EXTRACTED COMPONENTS (FFT AMPLITUDES)				
Case	$7f_s - 6sf_s$		$7f_s - 8sf_s$	
	$6sf_s$	$8sf_s$	$6sf_s$	$8sf_s$
Healthy	-47.54 dB	-47.16 dB	-47.54 dB	-47.65 dB
Faulty	-27.42 dB	-32.48 dB	-27.03 dB	-31.91 dB

The amplitudes of the examined components at $6sf_s$ and $8sf_s$ frequencies (circled in dashed in Fig. 8) rise at the amplitudes of -27.42 dB and -32.48 dB respectively, regarding the lower 7th harmonic's sideband (Table V). This implies a rise of 20.12 dB and 14.68 dB respectively, compared to the healthy motor. For the trajectory of the upper sideband, these spike at -27.03 dB and -31.91 dB respectively. Comparing with the healthy motor, this is rise of 6.42 dB and 5.68 dB respectively. Apart from the fact the 7th harmonic's sidebands provide a compelling diagnostic value for rotor faults with the proposed approach, it is also interesting to report that the impact of the component at $2sf_s$ is almost negligible for the 7th harmonic's sidebands (red arrows in Fig. 8).

TABLE VII
SLIP OF EXPERIMENTAL MOTORS (%)

healthy	0.028
faulty	0.024

V. CONCLUSION

This paper presented a newly introduced approach for the detection of rotor electrical faults in induction motors, ushering the presence of a subset of harmonic components in the low frequencies range of the stator current. These components are revealed by frequency extraction of the fault-related trajectories' spectral information in measured phase current signals. Taking advantage of the speed-ripple effect, the spectral density information $S(t, f_{a,i})$ is first extracted by STFT analysis for the a -th desired harmonic. Thereafter, each trajectory is treated as a periodical time signal and is evaluated with the classical FFT, to track and detect the modulations implied by the fault. The proposed diagnostic method has been applied on both FEM simulations' and experimental data with success, while offering reliable online and non-intrusive diagnostic potential.

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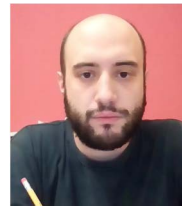
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